

BINAURAL LOCALIZATION OF PURE TONES

BY E. RUSSELL WIGHTMAN

University of Michigan

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN THE UNI-
VERSITY OF MICHIGAN

1930

BINAURAL LOCALIZATION OF PURE TONES

BY E. RUSSELL WIGHTMAN

University of Michigan

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN THE UNI-
VERSITY OF MICHIGAN

* 22412



BINAURAL LOCALIZATION OF PURE TONES

BY E. RUSSELL WIGHTMAN

University of Michigan

ABSTRACT

Pure tones of frequency 256 cycles per second were presented binaurally to eight different observers, the phase difference and amplitude ratio of the acoustical pressures at the two ears being known and adjustable. The observers were asked to state the direction and distance of the apparent source of sound. Only three of the eight observers were influenced in their judgment of direction by the phase difference and even they were rather inaccurate. All were influenced more or less in judging direction, by the amplitude ratio. None was able to tell the distance of the source by the amplitude ratio.

INTRODUCTION

While several experimenters have studied the relationship between the phase difference of a binaural stimulus and the direction of the apparent source, we are not aware that any have asked their subjects to state also the distance of the apparent source. As is shown below, it seems theoretically possible for the subject to judge the distance of the source, under certain circumstances, by a stereo-acoustic effect utilizing the amplitude ratio, much as the direction may be determined by the phase difference. It was this connection between the amplitude ratio and distance which we tested, incidentally obtaining additional data on the relation between phase difference, amplitude ratio and direction.

In Fig. 1 are shown the amplitude ratio and phase difference of the sounds at the two ears due to a real source of sound of frequency 256 cycles per second, placed at a direction or azimuth as indicated by the abscissae and at distances from the center of the head as marked on the curves. The azimuth is measured from the front toward the rear. These curves were obtained by measurement* of the sounds entering the ears of a man shaped dummy and agree well with the curves computed by Hartley and Fry on the assumption that the head is a rigid sphere in free space. (The amplitude ratio should not be confused with the intensity ratio which is often used in plotting curves of this nature; the intensity ratio is the square of the amplitude ratio.)

The phase difference depends on the azimuth, but its dependence on the distance of the source is slight and, due to the random reflection of sound from the shoulders, is erratic. Thus at this frequency, if we knew the phase difference of the binaural stimulus we could, by referring

* See preceding paper by F. A. Firestone.

to the curve, find the azimuth of the source with an uncertainty of about 5 degrees near azimuth 0, and plus or minus 25 degrees near azimuth 90. We would be unable to distinguish between front and rear since, for instance, azimuths 20 and 160 degrees give the same phase

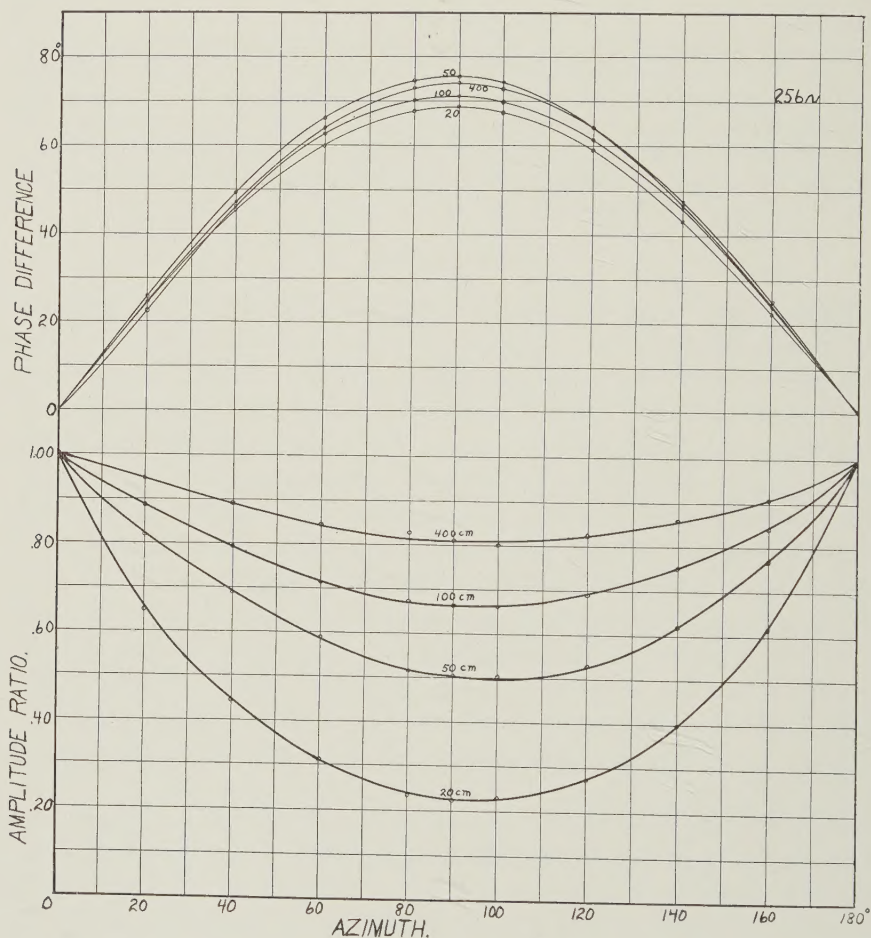


FIG. 1. Results of measurements at 256 cycles.

difference. Except for this ambiguity there is as shown by the curve, a simple relationship between the phase difference of the binaural stimulus and the direction of the source which produces it and therefore a proper appreciation of the phase difference by the ears would enable the direction of the source to be recognized.

There is also a relation between the amplitude ratio and the dis-

tance of the source, although this relation is not a simple one since the amplitude ratio depends on both the distance and direction of the source. But if a knowledge of the phase difference has already enabled a determination of the direction of the source, then the further knowledge of the amplitude ratio of the binaural stimulus enables the distance of the source to be determined. But even without a knowledge of the direction of the source, a knowledge of the amplitude ratio would enable a certain limiting distance to be determined as, for instance, an amplitude ratio of 0.40 would indicate that the source was certainly within 50 cm. of the head. The curves show that this method of determining the distance of a source can be accurate only when the source is within about 100 cm. of the head and at the side, as it is only then that the amplitude ratio changes appreciably with the distance of the source. At greater distances, the distance of the source of pure tone cannot be determined unless its intensity is known, in which case the distance is estimated by the loudness at the point of observation.

Thus the curves of Fig. 1 show the following relationships between the two physical characteristics of the binaural stimulus and two coordinates of position of the source: phase difference is a function of azimuth, amplitude ratio is a function of both azimuth and distance. With the knowledge contained in Fig. 1 we may make certain predictions as to the limitations of binaural localization as, for instance, we may be sure that distance cannot be determined by phase difference and that the determination of the direction of sounds of this pitch around azimuth 90 degrees will be very inaccurate. We can also predict that the amplitude ratio tells little concerning the direction of the source since at this frequency and for the source at a distance, the amplitude ratio differs very little from unity at all azimuths. The ears cannot determine information which is not contained in the stimuli which they receive. But, on the other hand, they may not appreciate all the information which is contained in the received stimuli. In these experiments we attempted to determine the ability of naive observers to localize the synthetic tone of 256 cycles per second which was presented to them, paying particular attention to their ability to tell the distance by the amplitude ratio.

APPARATUS

The sounds were presented to the observer by means of a telephone receiver on each ear. An ordinary type of high resistance receiver was used but a shim was placed under the diaphragm so as to increase the

air gap, thereby gaining greater constancy of sensitivity and freedom from distortion. To the receiver cap was attached a small box having a volume of 5 cc. and a tip such as is usually found on stethoscope binaurals (see Fig. 2). The purpose of the small box was to increase the total volume in front of the diaphragm so that small changes in volume during the experiment would be unimportant. Different shapes of tips were used so that a snug fit could be achieved on all observers.

The receivers were supplied with sine wave voltage of frequency 256 by the circuit shown in Fig. 2. A vacuum tube oscillator with band

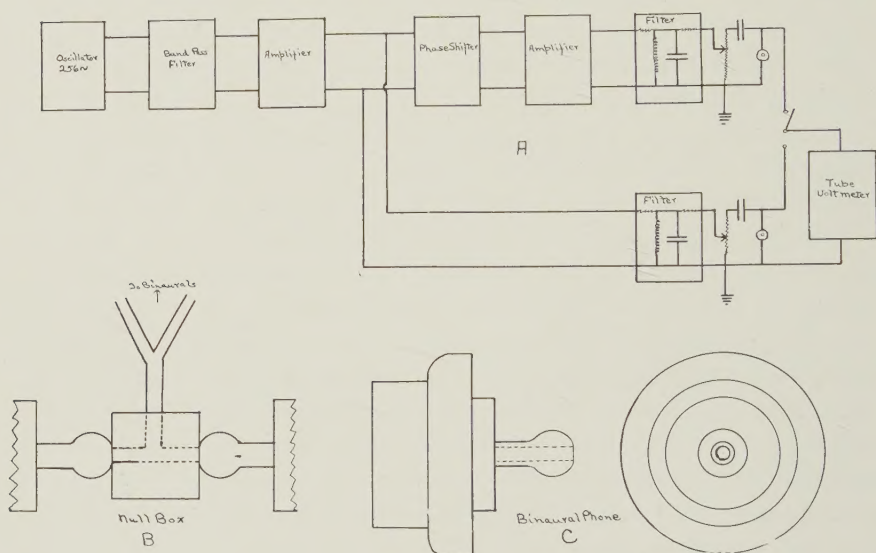


FIG. 2. *Apparatus used for Binaural Localization of Pure Tones.*

pass filter feeds into a UX 250 amplifier. The output of this amplifier is divided, part going directly through a filter circuit and potentiometer to one phone, while the other part goes through the phase shifting device and a filter to the other phone. This phase shifting device is the same as described elsewhere by one of us [F. A. Firestone, *ibid.*] and is capable of producing a known and adjustable phase shift which is controlled by the setting of a single dial. The magnitude of the voltage output from the phase shifter does not depend on the phase setting. The filters which are used just ahead of the phones consist of a single anti-resonant circuit with appropriate series resistors. A condenser of suitable value was placed in series with the phones, and the potentiometer was so designed that the phase of the voltage across the phone

was not changed when its magnitude was altered by varying the potentiometer. A tube voltmeter was used to measure the voltages across the phones.

On account of the difference in sensitivity and phase lag of the phones one cannot say that sounds of equal intensity and phase are produced by them when they are supplied with equal voltages which are in phase. To surmount this difficulty the sensitivity ratio and phase difference of the phones was determined by applying them to the null box shown in Fig. 2. This consists of a small soft rubber adapter by means of which the receivers may be symmetrically attached to the opening of a pair of stethoscope binaurals. With a constant voltage on one phone, the magnitude and phase of the voltage on the other phone is varied till no sound is heard in the binaurals. If the phase shifter is now turned 180 degrees we know that the sounds produced by the two receivers are in phase, and that if they are connected to equal volumes the resulting pressure amplitudes will be equal. The fact that the balance on the null box gave silence is considerable evidence that the sound produced by each phone is a pure tone, since it would be fortuitous that the harmonics should balance out at the same phase setting as the fundamental, especially when one notes the dissimilarity of the circuits through which the voltages for the two phones have come.

PROCEDURE

The observer, wearing the phones, sat in the center of a large room and indicated the position of the apparent source of sound by motioning to the experimenter, who adjusted a rod to the indicated position. The azimuth and distance of the rod were then recorded. At the beginning of each sitting the observer was handed the following written instructions.

You will listen to sound in the headphones. This sound will appear to come to you from a certain place in the room. As the operator makes certain changes the apparent distance and direction of the sound may change. No regular order will be followed in making these changes. The sound will probably appear to come from a point on the level of the head and may appear to be either several feet away or within a few inches of the head. You are to indicate to the operator the exact point from which the sound appears to come to you.

Do not be discouraged if you are unable to locate the position of the source with certainty. In case of doubt make the best guess you can and tell the operator that you are guessing.

The experimenter did not discuss the experiment further with the observer. The instructions clearly suggest what we wish the observer to hear, but the observer knows nothing of the nature of the changes in binaural stimuli which the experimenter is making, so that the only

way in which the observer can obtain a consistent and smooth relation between his position coordinates and the experimenters phase differences and amplitude ratios is for him to make use of his binaural sense.

All the observations reported in this paper were made at a frequency of 256 cycles per second. The following phase differences were used: -90 , -70 , -40 , -20 , 0 , 20 , 40 , 70 and 90 , the minus sign indicating that the phase of the sound in the left ear is leading. Phase differences larger than 90 degrees were not used since the curves of Fig. 1 show that 75 degrees is the largest phase difference which can arise due to an actual source having this frequency. The following amplitude ratios were used: -0.12 , -0.25 , -0.50 , 1.00 , 0.50 , 0.25 , 0.12 , the minus sign indicating that the amplitude at the left ear is greater. Each phase difference was used from seven to ten times with each amplitude ratio for each observer. For convenience, the amplitude ratio was kept constant while each of the phases was presented twice in a random order. Another ratio was then set and the list of phases again presented twice in another order. On later days the observations on a given ratio would be repeated so as to give the total number of observations indicated above. Eight observers were used, none being familiar with the theory of binaural phenomena. In changing the amplitude ratios, the amplitude in one ear was maintained at the value which was used for ratio 1.00 while the amplitude in the other ear was reduced to the ratio desired. The amplitude used at ratio 1.00 was about 60 decibels above the threshold. The phones were always disconnected while changes were being made.

In order to get a direct test of the possible influence of the amplitude ratio on the apparent distance of the sound, a further test was made in which the phase difference was set for 70 or -70 degrees, the value which it would have for a source at the side, and the amplitude ratio was varied to all the above values. In this experiment the observer was given the following additional instructions.

The sound will now appear to come directly from the right or directly from the left. You are to state from which side it appears to come and from what distance.

RESULTS

While the work of certain other investigators has seemed to indicate that the direction of a pure tone could be quite accurately determined by the phase difference by most observers, only three of our eight observers were appreciably influenced by the phase difference in their estimation of direction and even these were inconsistent with them-

selves from day to day. Most of them were influenced more or less by the amplitude ratio in estimating the direction. None was able to obtain any consistent judgment of distance by the amplitude ratio. Some of the observers localized some of their sources in the rear, but all of the observations which have been plotted in this paper were localized in front.

Observer *S* gave the most consistent results of all the observers for phase difference versus azimuth, his observations being plotted in Fig. 3. In each graph of Fig. 3 phase difference of the binaural stimulus is plotted vertically and azimuth of the apparent image horizontally. The different graphs are for the different amplitude ratios as marked in the upper corners. The points represent single observations. According to the data of Fig. 1 the relation between phase difference and azimuth for ratio 1.00 (which corresponds approximately to a source at a great distance) is as shown in the graph in the upper left of Fig. 3. The actual observations for observer *S* agree roughly with this theoretical curve statistically, but the individual observations are quite dispersed. In going to different amplitude ratios the average observation was slightly shifted in azimuth but the phase difference was still the controlling factor in determining the direction. It should be noted that the combination of positive phase difference and negative amplitude ratio and vice versa could not be produced by an actual source so that the upper half of the negative ratio graphs and the lower half of the positive ratio graphs represent the observers' response to binaural stimuli which are inconsistent with themselves. Part of the data on amplitude ratio versus distance for observer *S* are plotted in the second row of graphs in Fig. 4. The two graphs are for phase differences of -70 and 70 degrees which correspond to a source at the side, amplitude ratio of the binaural stimulus being plotted as abscissae and distance in centimeters of the apparent source from the center of the head as ordinates. According to the data of Fig. 1 the relation between amplitude ratio and distance is as shown in the upper graphs of Fig. 4. Here also, the right side of the negative phase graphs and the left side of the positive phase graphs represent the response of the observer to binaural stimuli which are inconsistent with themselves. These data were chosen from the regular run in which the phase difference and amplitude ratio were both varied, and not the special experiment in which the phase difference was kept constant while the amplitude ratio was varied. As shown in the graphs, observer *S* localized all the sounds near the head and his estimate of distance was not appreciably changed by

changes in amplitude ratio. His observations at other phase differences were similar.

Observer *T* gave observations on phase difference versus azimuth which were less consistent than for observer *S*; his results are shown in Fig. 5. At amplitude ratios of 1.00 and .50 his judgment of direction was obviously influenced by the phase difference, although to a lesser extent than one would expect from looking at the theoretical curve. At ratios of .25 and .12 he scarcely recognized the changes of phase difference but localized the sound on the side having the greater amplitude. His judgments of distance, of which the lower graphs of Fig. 4 are typical, showed no relation to the theoretical curve. Observer *O* gave results of the same nature as observer *T*. (Not plotted.)

Observer *WR*, a schoolboy about 15 years old, shows practically no phase effect whatever, see Fig. 6. He localizes the sound on the side having the greatest amplitude and at an azimuth which depends on the amplitude ratio. As shown in Fig. 4, amplitude ratio did not affect his judgment of distance to any great extent.

Observer *C* placed all images in the immediate vicinity of azimuth -70 or 70 degrees and obtained no images in front, or closer to the front than 50 degrees. He was not in the least influenced by phase difference. For ratio 1.00 he placed about an equal number of images on the two sides. For ratio .50 he placed about twice as many on the side of greater amplitude as on the side of lesser amplitude. For ratios .25 and .12 he placed all images on the side having the larger amplitude. He estimated all distances as about 75 cm. regardless of amplitude ratio.

Observer *R* showed only a slight phase effect but was appreciably influenced in his judgment of direction by the amplitude ratio although his observations were even more dispersed than those of *WR*. His estimation of distance was erratic.

Observers *W* and *Z* were just able to tell right from left when the amplitude ratio was .12 or .25 but otherwise they showed no evidence of being able to localize at all. They had no phase effect. Only the typical results of Fig. 4 on amplitude ratio versus apparent distances have been published although we obtained a large amount of similar data. Several of the observers showed a tendency to ascribe greater distance to those amplitude ratios around .12 than to ratio 1.00, similar to the observations of *T*, Fig. 4. This may be explained as due to the fact that the ratios were changed by decreasing the amplitude in one of the ears from the value which it had for ratio 1.00 so that the sum of the amplitudes in the two ears was less. The observer then sub-

consciously assumed that the reduction in loudness had come from the removal of the source to a greater distance. This effect was somewhat more pronounced in the special experiment in which the amplitude ratio only was varied while keeping the phase constant; since in this case the ratios were changed more rapidly, the observer recognized the apparent change in total intensity more easily. The truly binaural amplitude ratio effect, which would have caused localization of ratio .12 within a few centimeters of one ear, apparently did not exist for any of the observers.

DISCUSSION

One reason why there has been so much controversy on the question of binaural hearing is illustrated by the individual differences shown in our data. Observer *S* had good phase effect and almost no intensity effect. *WR* had a marked intensity effect and practically no phase effect. *T* and *O* were midway between these two extremes. *C* placed all images at the sides apportioning them according to the amplitude ratio, and had no phase effect. *W*, *Z*, and *R* has no phase effect and were scarcely able to localize at all. Apparently this is one of the acoustical problems with complex tones which cannot profitably be analyzed into a problem with pure tones.

It thus appears that the relation between phase difference of binaural stimulus and direction of the apparent source is, for pure tones, a rather indefinite and inaccurate one at best and that for many naive observers it does not exist. Supporting this indefiniteness of the phase effect of pure tones are the experiments of Willard L. Valentine (*Jour. Comparative Psychology*, VII Oct., 1927 pp. 357) on binaural beats who found that with a slow beat, of ten inexperienced subjects, none noticed the beat in 15 minutes of observing and that no rotation was observed by any subject except those to whom a rotation had been suggested. It may be that some experimenters have obtained more consistent data on phase difference versus direction because the tones which they used were not as pure as they thought. Our data do not prove that phase difference may not be an important factor in localization in everyday experience, as an observer might be able to localize a complex tone accurately while being unable to localize a pure tone. If the direction of low pitched complex tones at a distance can be determined, then the phase difference must be the informing factor since the intensity ratio for low pitched tones at a distance does not appreciably depend on the direction of the source. Also in binaural devices for submarine detection

the connection between phase difference and apparent direction is utilized. It therefore seems highly probable that phase difference is an important factor in localization of complex sounds although our observations show the inability of most observers to localize pure tones.

Since our observers were unable to tell the distance of the source by the amplitude ratio, it must be that the distance of a source is usually told by its loudness at the point of observation coupled with a knowledge of the intensity of the source, and cannot be ascribed to a stereo-acoustic effect which would necessarily depend on the amplitude ratio. The fact that the direction of the apparent source was for most of our observers changed by varying the amplitude ratio would seem to indicate that the observers were accustomed to relying on the amplitude ratio to some extent in judging direction at least, when the source was close enough that the amplitude ratio would differ considerably from unity. Since there is known to be no phase effect whatever for most observers above roughly 1000 cycles per second, if high pitched tones can be localized at all, then the amplitude ratio (of each component) must be the informing factor.

APRIL, 1930

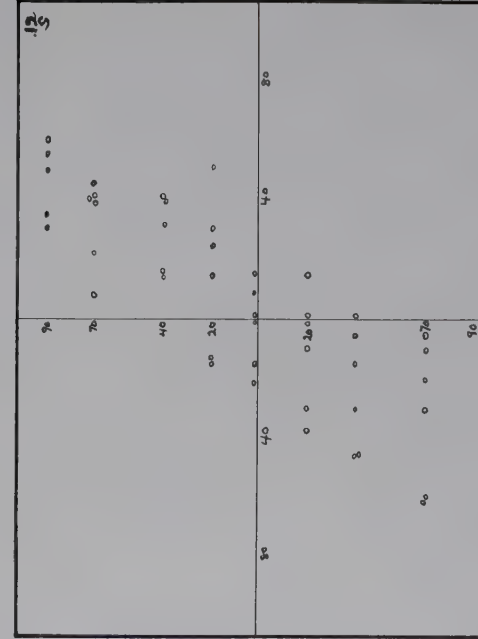
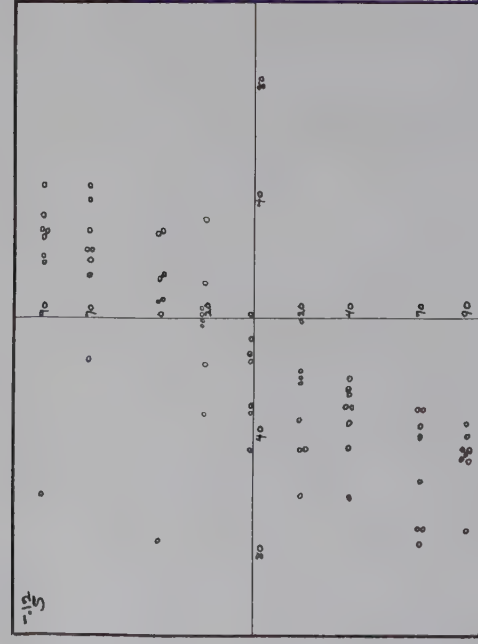
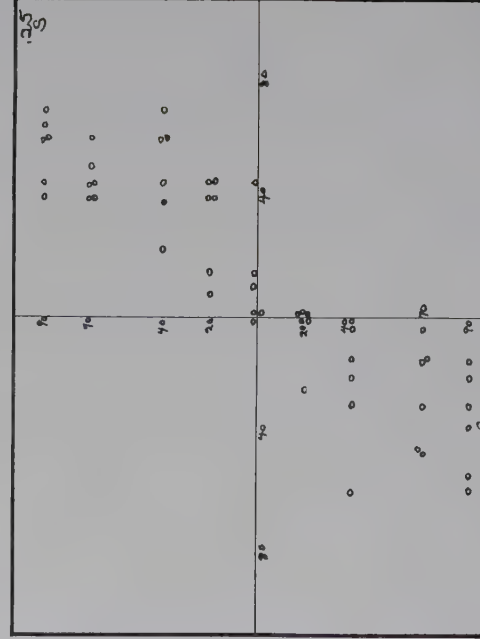
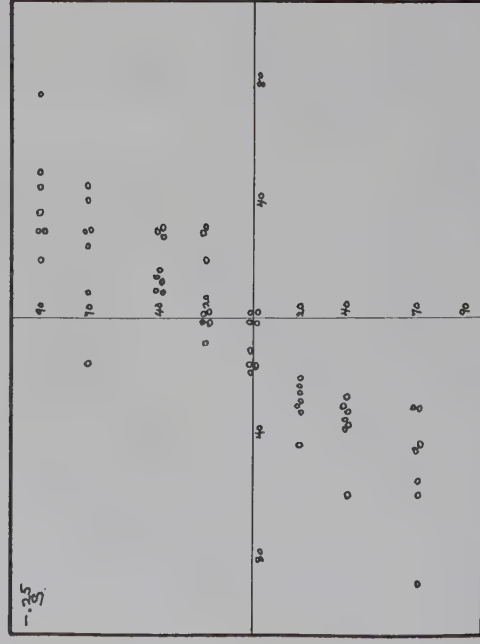
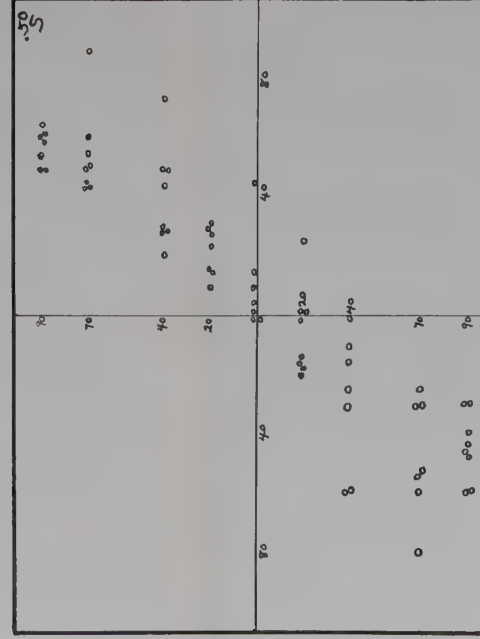
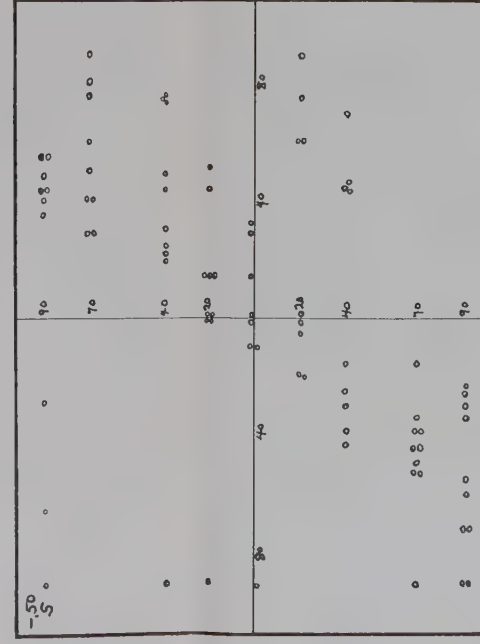
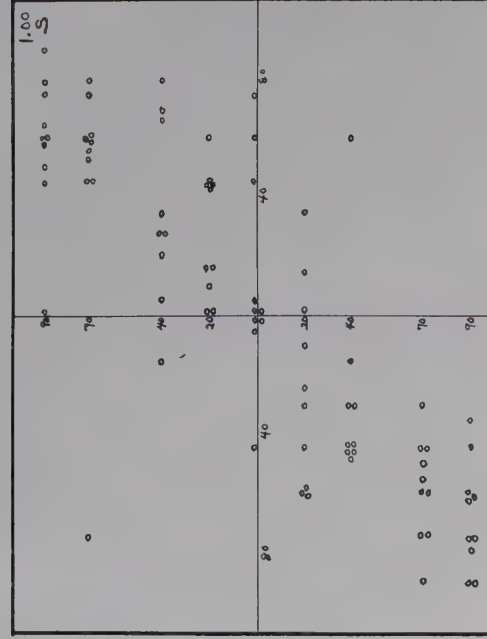
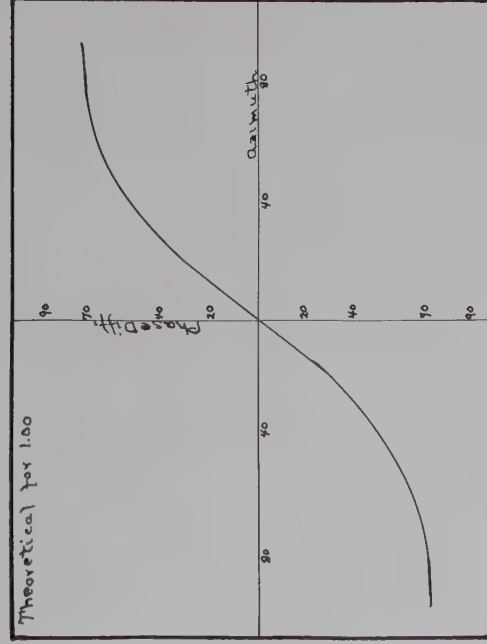
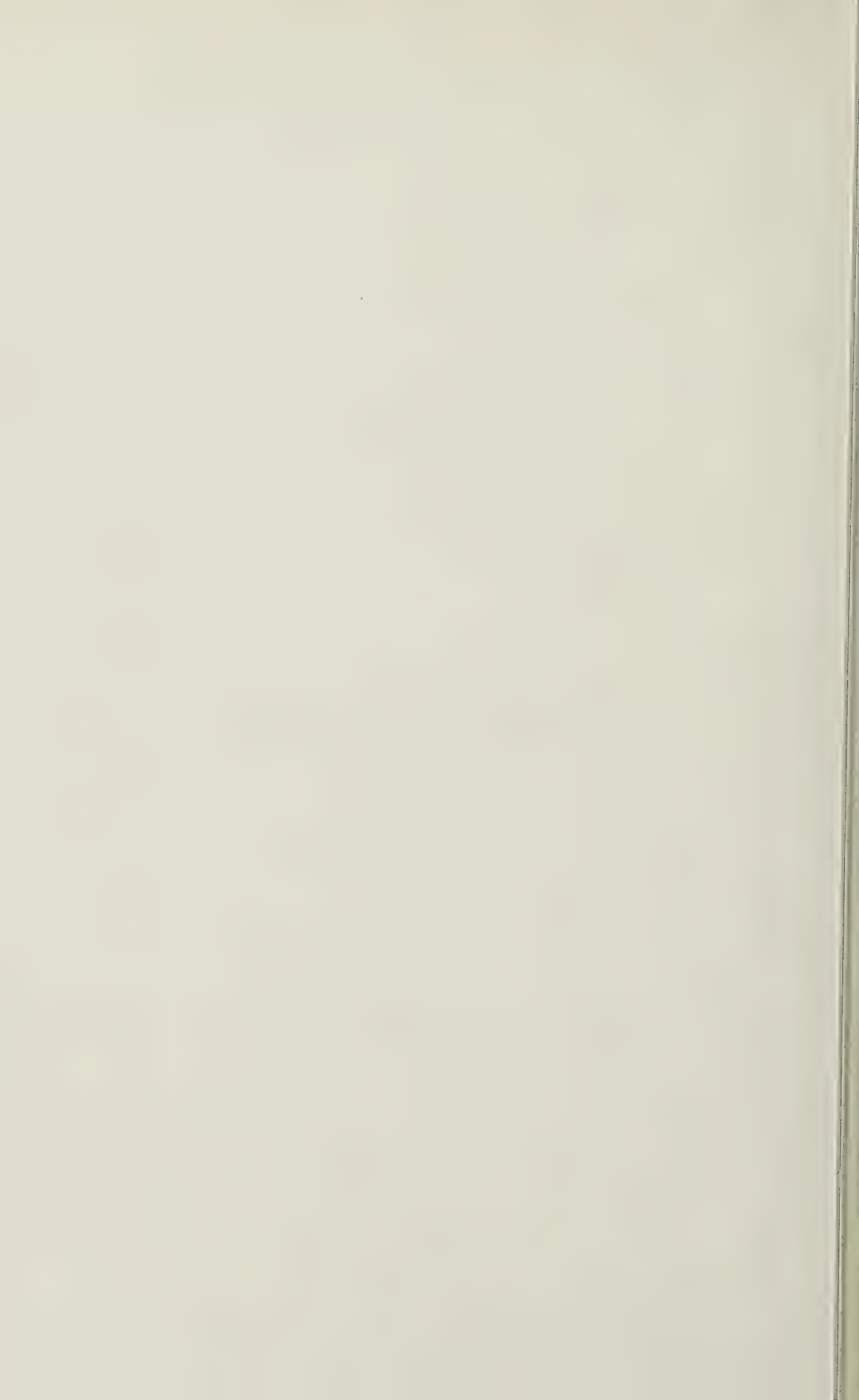


FIG. 3.



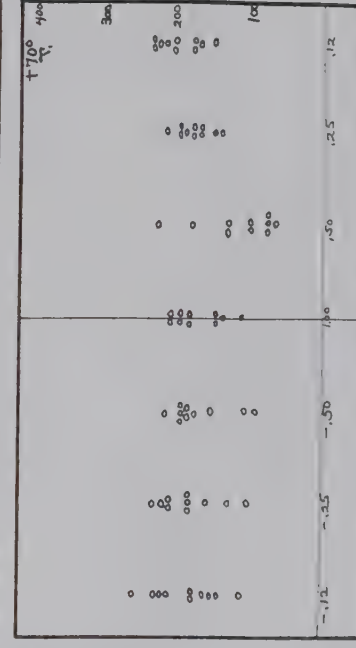
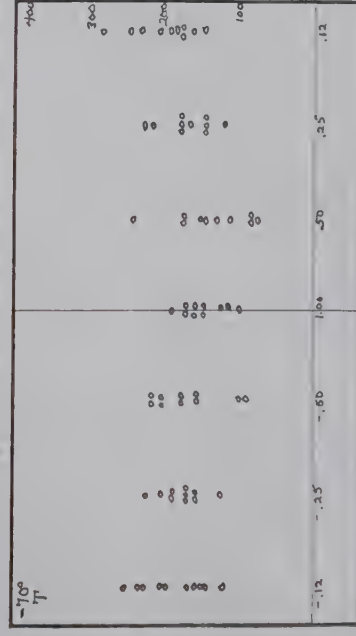
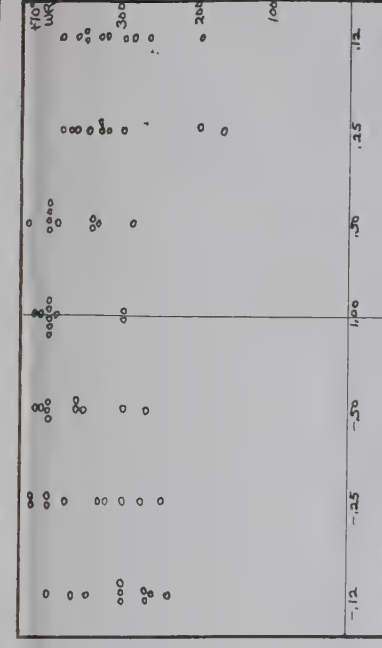
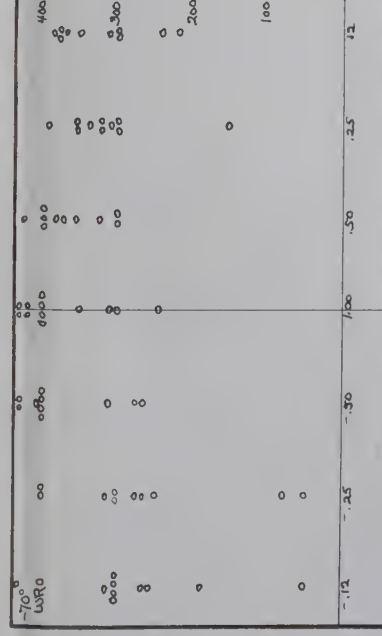
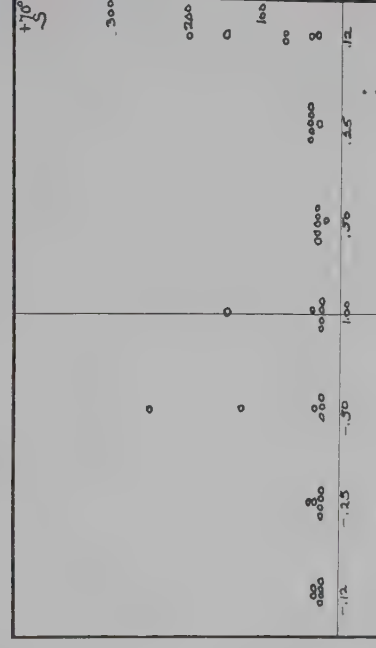
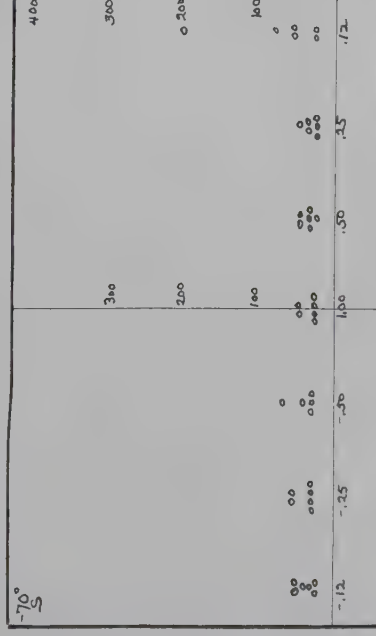
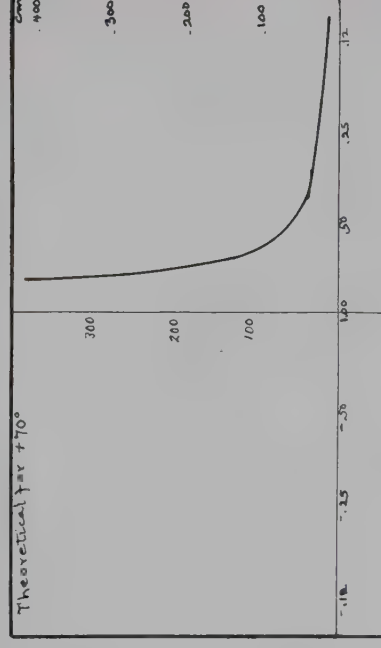
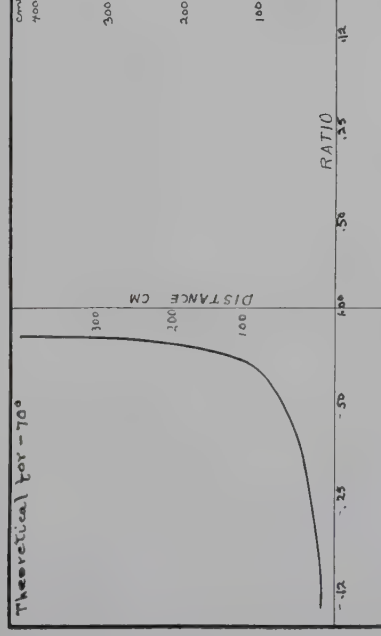


FIG. 4.

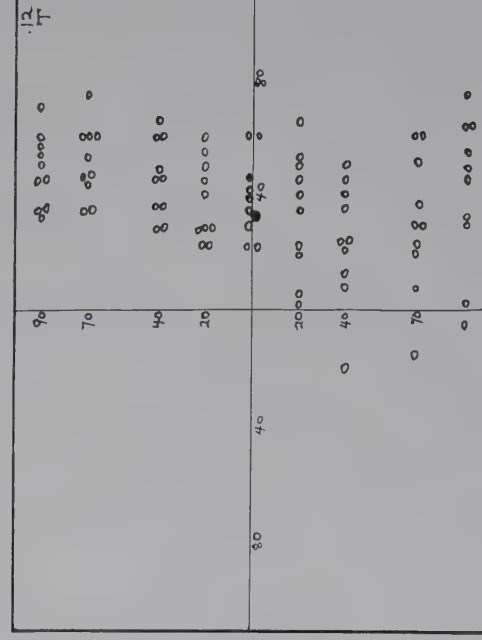
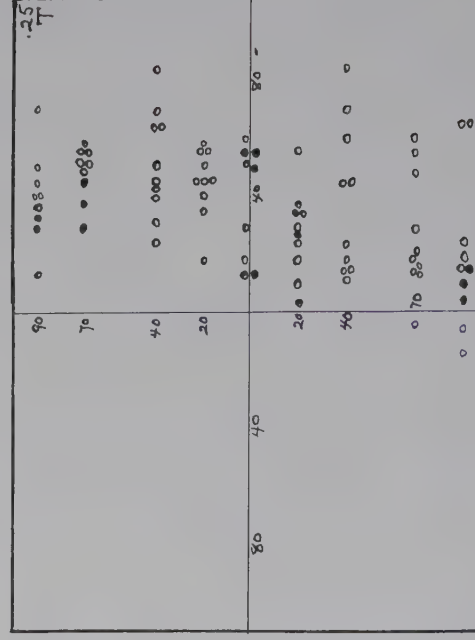
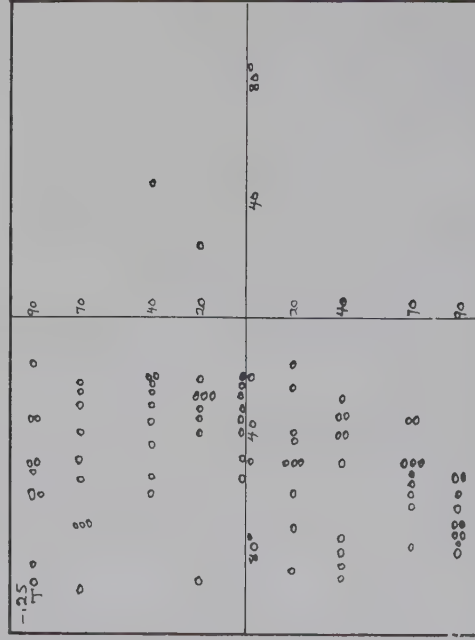
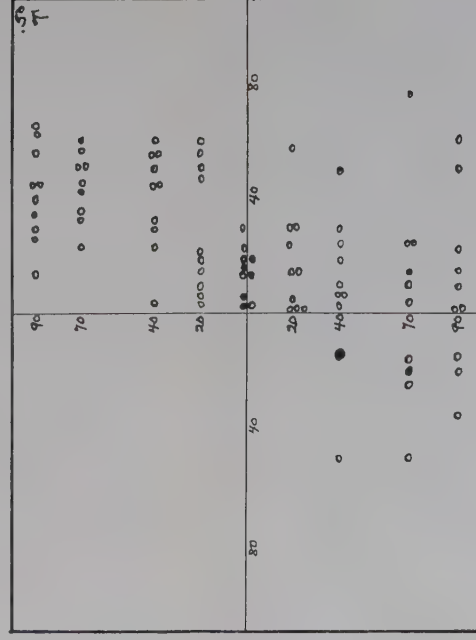
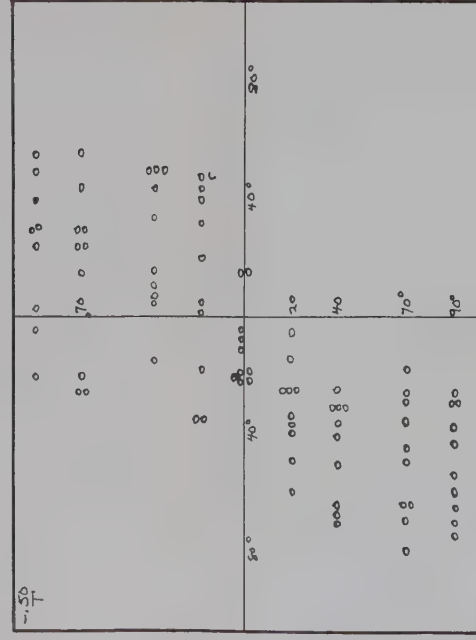
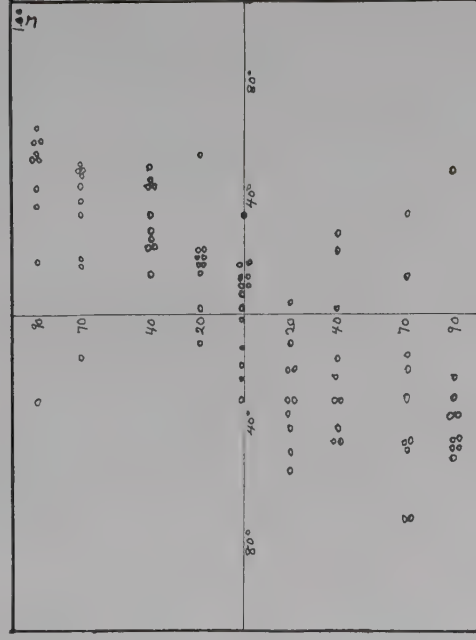
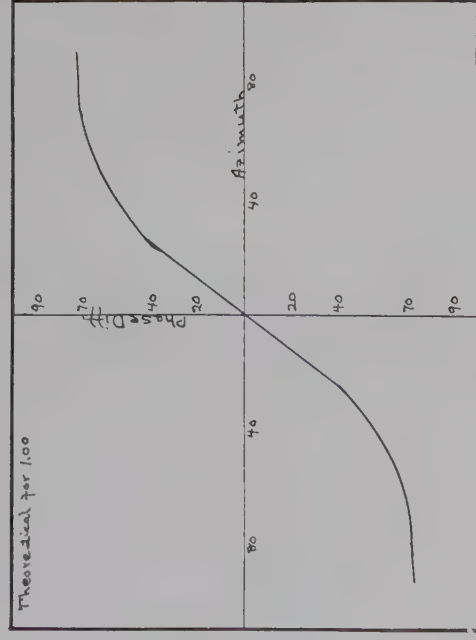


FIG. 5.

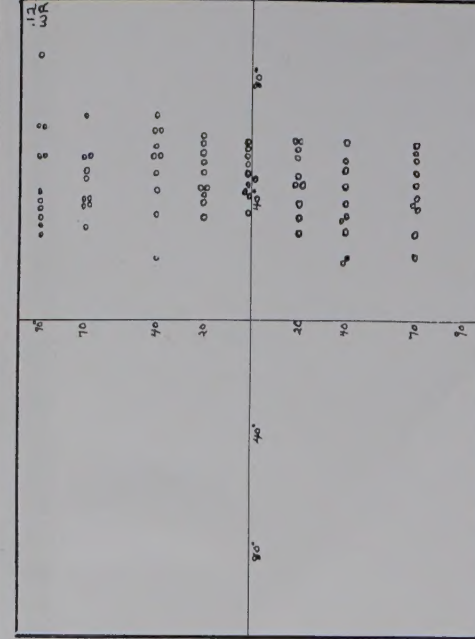
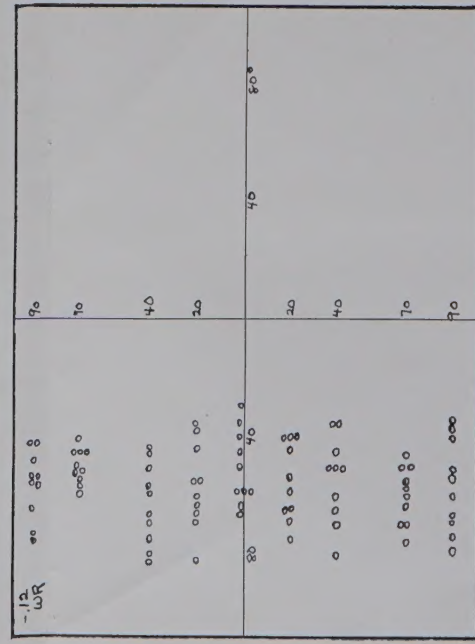
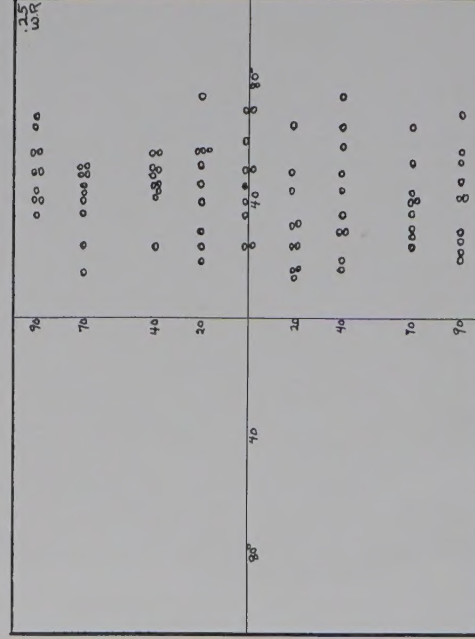
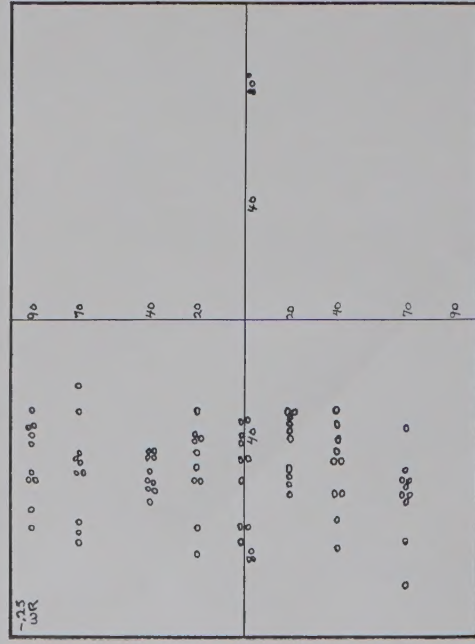
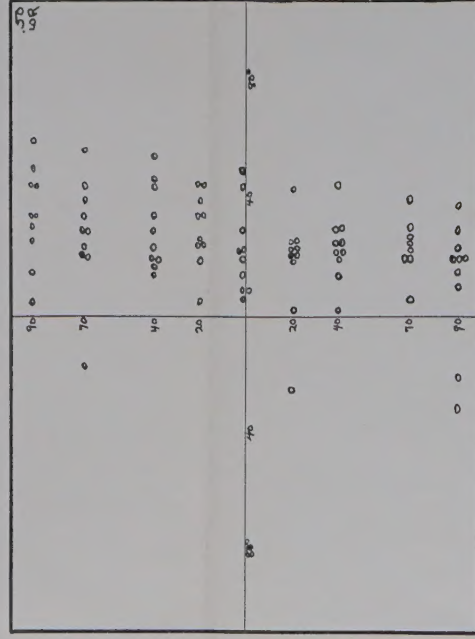
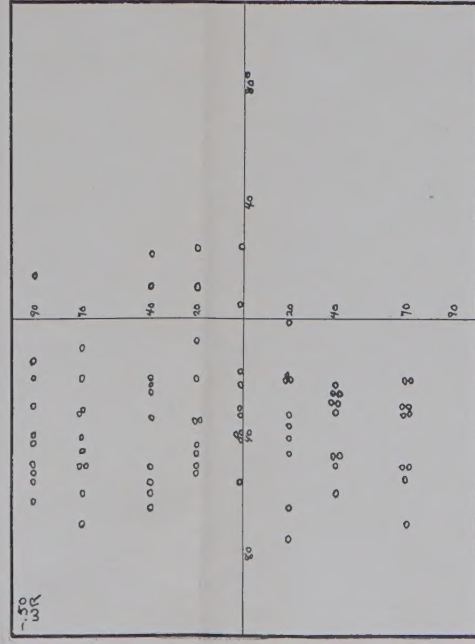
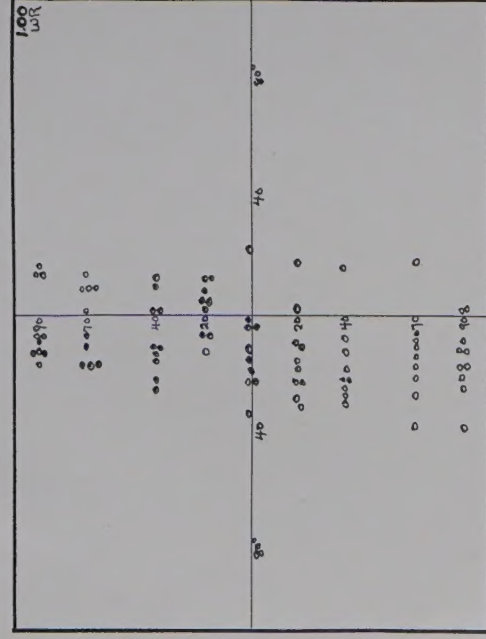
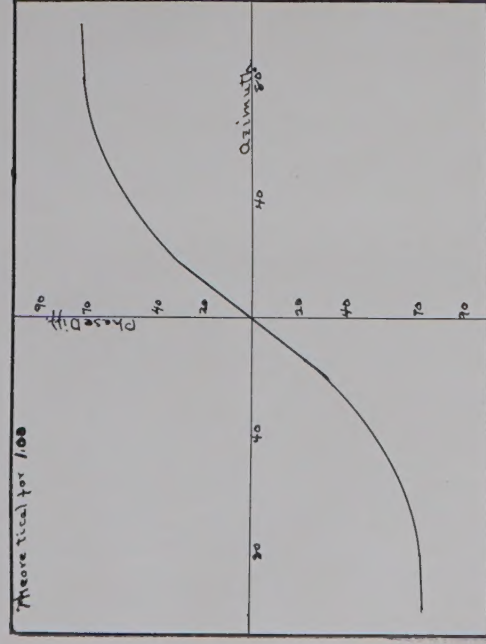


FIG. 6.

